

Empirical Formalism For Projectile Fragmentation and Production of New Neutron-rich Nuclei with RIBs

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Abstract

The Projectile Fragment Separator type radioactive ion beam (RIB) facilities, being developed in different laboratories, provide the scope for producing many new exotic nuclei through fragmentation of high energy radioactive ion (RI) beams. A new empirical parametrization for the estimation of cross-sections of projectile fragments has been prescribed for studying the advantages and limitations of high energy RI beams for the production of new exotic nuclei. The parametrization reproduces the experimental data for the production of fragments from neutron rich projectiles accurately in contrast to the existing parametrization which tends to overestimate the cross-section of neutron rich fragments in most cases. The modified formalism has been used to compute the cross-sections of neutron-rich species produced by fragmentation of radioactive projectiles (RIBs). It has been found that, given any limit of production cross-section, the exoticity of the fragment increases rather slowly and shows a saturation tendency as the projectile is made more and more exotic. This essentially limits, to an extent, the utility of very neutron-rich radioactive beams vis-a-vis production of new neutron-rich exotic species.

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I. INTRODUCTION

Synthesis of many new β -unstable nuclei and production of such nuclei with appreciable yield for structure studies and other experiments are becoming feasible with the advent of Radioactive Ion Beam (RIB) facilities and related activities in many laboratories [1], all over the world, for different kinds of facilities following different routes of nuclear reactions.

Existing high energy heavy ion accelerators provide the opportunity for producing β -unstable nuclei through Projectile Fragmentation (PF) reactions with stable projectiles. Projectile fragments Separator (PFS) technique, as adopted by different laboratories [2] provides RIBs of high energies suitable for production of more exotic nuclei through PF reaction of secondary unstable projectiles. Reliable estimation of yields of these exotic nuclei produced by fragmentation of secondary RI projectiles is very important for assessing the advantages and limitations of RIBs towards production of new exotic species.

Estimation of the production cross-sections new exotic species, especially of the n-rich nuclei, through PF reactions of RIBs is our topic of interest for this article. It is worth mentioning that similar exercises on production of exotic nuclei with RIBs through multinucleon transfer reactions and CN-evaporation reactions, the other two important reaction mechanisms for production of exotic nuclei, have already been addressed [3].

In this article we have attempted to develop an empirical formalism for the estimation of fragments' cross-sections from RI projectiles and for this purpose we started with the well studied target fragmentation processes. Target fragmentation cross-sections have been measured for various experimental conditions. Empirical parametrization to fit the experimental mass and charge yield $\sigma(A,Z)$ was initiated by Rudstam [4] and has thereafter been elaborated by many others [5,6]. The formalism of Summerer et al [6] is now widely used to predict the cross-sections of projectile fragments in PF reactions[7], since this reaction can be considered, in the projectile rest frame, in the same footing as that of target fragmentation in the target rest frame.

The parametric expression of Summerer et al can reproduce the experimental cross-sections of projectile fragments quite accurately only if the fragments are not too exotic and the projectile is the most β -stable one, e.g. ^{40}Ca instead of say ^{48}Ca . This can be clearly seen from Fig. 1, where the cross section data [8] for $^{21-24}\text{O}$, $^{23-25}\text{F}$, $^{25,29}\text{Ne}$, $^{29-35}\text{Na}$, $^{34-38}\text{Mg}$, $^{35-41}\text{Al}$, $^{41-45}\text{Si}$ from $^{48}\text{Ca} + ^{181}\text{Ta}$ at 70 A MeV reaction are represented along with the estimations by the formalism of Summerer et al. It can easily be seen that the formalism overestimates the cross-sections of exotic (n-rich) fragments. Hence this formalism can not be used to predict reliably the cross-sections of even more exotic

n-rich fragments produced in PF reactions of n-rich exotic projectiles (RIBs). One thus needs to develop a modified empirical formalism if one aims at a fairly accurate prediction of the cross-sections of new n-rich nuclei which can hopefully be produced with n-rich radioactive projectiles.

The organization of the paper is as follows : Section II of this paper has been devoted for a brief description of the empirical parametrizations, and the modifications that have been carried out in this work; results and conclusions are discussed in sections III and IV respectively.

II. EMPIRICAL PARAMETRIZATION OF FRAGMENTATION CROSS-SECTIONS.

The analytical formulae for the yield distribution as a function of the fragment mass and charge $\sigma(A, Z)$ is conventionally written as,

$$\sigma(A, Z) = [Y(A)].[n \exp(-R|Z_P - Z|^U)]. \quad (1)$$

The first term $Y(A)$ represents the mass yield, i.e. the sum of the isobaric cross-sections with mass A , while the second term describes the charge dispersion around its maximum Z_P . R is the width parameter, which actually controls the shape of the charge dispersion and U its exponent. The factor n simply serves to normalize the integral to unity.

Abu-Magd, Friedman and Hufner [9] have shown that for relativistic proton induced reactions one obtains the functional form of $Y(A)$ from multiple scattering and an approximation to the evaporation chain for spallation as :

$$Y(A) = \sigma_R P(A_P) \cdot \exp[-P(A_P)(A_P - A_F)], \quad (2)$$

where the best fitted slope parameter $P(A_P)$ is written as :

$$\ln P(A_P) = -7.57 \times 10^{-3} A_P - 2.584. \quad (3)$$

The factor σ_R is chosen as the sum of the target and projectile radii rather than the square of the sum as :

$$\sigma_R = 450(A_P^{1/3} + A_T^{1/3} - 2.38), \quad (4)$$

where A_P and A_T denote the projectile and target mass numbers respectively.

Furthermore, in order to get the distribution of nuclear charge, Z , for a given fragment mass number A ., three parameters (in Eqn.1) R , Z_P and U must be known. Since these three parameters are strongly correlated, it is really difficult to have unique estimation with a least-square fitting technique and hence people have chosen instead to fix first the exponent U and then best fitted values of Z_P and R were obtained by fitting the data.

It is important to mention that all the presently available data indicates that Rudstam's early suggestion, $U = 1.5$ gives a very good description in the n-rich side of the distribution, whereas the p-rich side of the distribution falls off like a Gaussian with $U=2$. But for strictly symmetric charge dispersion, the values of U may be taken in between 2 and 1.48.

The width parameter R which is a function of fragment mass only, irrespective of the projectile nucleus, has been approximated with an exponential of the form as :

$$\ln R(A_F) = -6.770 \times 10^{-3} A_F + 0.778. \quad (5)$$

In general, the parametrization of Z_P is very important. Several parametrization have already been performed and from their analyses for the fragmentation cross-sections the conclusions can be summerized as follows :

1. For stable projectile, the maximum of the charge distributions are always on the neutron-deficient side of the valley of β -stability.
2. For projectile close to β -stability Z_P is a function of the fragment mass only.
3. For more n-rich or p-rich projectile the fragments remember the neutron or proton excess of the projectile to varying extents (the so called memory effect).

Following the idea of Chu et al [10], (where Δ has been considered to take into account the n- or p-richness of the fragments) Summerer et al has finally landed up with the following expression of Z_P as :

$$Z_P(A_F) = Z_\beta(A_F) + \Delta + \Delta_m, \quad (6)$$

where $Z_\beta(A_F)$ is approximated by a smooth function [11] as :

$$Z_\beta(A_F) = A_F / (1.98 + 0.0155 A_F^{2/3}) \quad (7)$$

and the differences Δ and Δ_m have been parametrized as,

$$\Delta = 2.041 \times A_F^2 \times 10^{-4} \quad A_F \leq 66, \quad (8)$$

$$\Delta = 2.703 \times A_F \times 10^{-2} - 0.895 \quad A_F \geq 66, \quad (9)$$

$$\Delta_m = [C_1 (A_F/A_P)^2 + C_2 (A_F/A_P)^4] \Delta_\beta(A_P), \quad (10)$$

with

$$\Delta_\beta(A_P) = Z_P - Z_\beta(A_P). \quad (11)$$

$C_1 = 0.4$, $C_2 = 0.6$ are assigned for n-rich projectile, while for p-rich $C_1 = 0.0$, $C_2 = 0.6$. The factor Δ_m was introduced to take care of the 'memory effect', that is the effect of the exotocity of the projectile on the fragment production cross-sections. However, it is more appropriate and aesthetically appealing to introduce exotocities of the projectile and the fragment directly in the expression for the charge distribution instead of the parameter Δ and Δ_m to take care of the memory effect.

Keeping in mind that the drip line is closer to the β -stability line at lower Z and moves more and more away as Z increases, we define the exotocity of the projectile and fragment as,

$$\rho_F = \frac{A_F - A_F^s}{Z^F} \quad (12)$$

and

$$\rho_P = \frac{A_P - A_P^s}{Z^P}, \quad (13)$$

where Z^F and Z^P are the atomic numbers of the fragment and the projectile respectively. $A_F(A_P)$ is the mass number of the fragment (projectile) and $A_F^s(A_P^s)$ is the mass number of the β -stable isotope corresponding to $Z^F(Z^P)$.

ρ_F and ρ_P are added in the expression of most probable charge Z_P as $0.8\rho_F - 2.\rho_P$, that is with opposite signs. This is because more exotic projectile should favour production of more exotic fragments whereas the production cross-section of fragments from a given projectile should decrease as the fragment becomes more exotic.

We have taken care of the 'memory effect' through the exotocity parameters ρ_P and ρ_F . However, to have the centroid perfectly at $A_F = A_F^s$ for $A_P = A_P^s$ we have added the factors Δ^s and Δ_m^s in the expression for the most probable charge Z_P , where Δ^s and Δ_m^s are the values of Δ and Δ_m on the β -stable line and are calculated from equations (8), (9) and (10) by substituting $A_F = A_F^s$ and $A_P = A_P^s$. For $Z \leq 40$, A_F^s and A_P^s are calculated using the expression :

$$A^s = 2.08Z + 0.0029Z^2 + 7.00 \times 10^{-5}Z^3, \quad (14)$$

which is a slightly modified form of the expression used by Charity et al [12] earlier.

To have a right match with the experimental data the width parameter R and the exponent U have been adjusted in our formalism as,

$$\ln R = -6.770 \times 10^{-3} A_F + 24.11 \times 10^{-2} (A_P - A_F)^{1/3} \quad (15)$$

and $U = 1.57$ instead of 1.5 used by Summerer et al for n-rich fragment while for p-rich side $U=2$, with the normalisation factor $n = \sqrt{\frac{R}{\pi}}$.

The $(A_P - A_F)^{1/3}$ dependence of the width parameter R is a new addition and has been introduced since intuitively the isospin fluctuation should become less and less probable as bigger and bigger chunks/portions of the projectile are removed from the projectile. These implies that the width (R^{-1}) of the charge distribution should decrease as the fragment becomes more and more lighter as compared to the projectile.

To take care of the fact that projectiles beyond the n-drip line are unrealistic and can not therefore lead to an enhancement of cross-section for the production of exotic species, we have introduced a factor,

$$\xi^d = 1.22 \times \frac{A_P^d - A_P^s}{Z^P} \quad (16)$$

in the expression of the most probable charge Z_P . A_P^d is the mass number at the drip line corresponding to the projectile's charge number Z^P . A_P^d 's are decided on the basis of the mass formula by Janeeke-Masson [13]. The factor ξ^d has been considered only for cases where the projectile is beyond the n-drip line. It is important to note ξ^d is, but for the constant factor 1.22, just the value for the exoticity at the drip line corresponding to Z^P .

The same expression and parametrization [equations (2), (3) and (4), ref. 6] for the mass yield $Y(A)$ has been used in our formalism. Thus the target dependence of the fragmentation cross-section has been taken care only through equation (4).

The final form of our expression thus becomes,

$$\sigma(A, Z) = Y(A).n.exp[-R|Z_\beta + \Delta^s + \Delta_m^s + 0.8\rho_F - 2.\rho_P - \xi^d - Z|^U] \quad (17)$$

with $Y(A)$ given by eqn.(2).

III. RESULTS.

Fig.1 shows a comparison of the modified parametrization with the older one along with a number of experimental values of cross-sections of various fragments with different exoticities for the nuclear reaction : $^{181}Ta(^{48}Ca, X), E(^{48}Ca) = 70$ A MeV (ref.8). The dotted lines show the results of the earlier [6] parametrization while the solid zig-zag lines join the experimental data points. The modified parametrization has been shown by solid lines. The modified relationship gives excellent match with that of the experimental data and obviously a much

better match compared to the earlier one which is depicted in Fig.1. A better fit has always been obtained for more exotic species. However, as has already been discussed, the earlier parametrization as well as the present one give similar results for less exotic fragments produced from less exotic projectile. This feature is clearly visible in Fig.2, where estimated cross sections for various fragments produced in the nuclear reaction : $^{181}\text{Ta}(^{50}\text{Ti}, X), E(^{50}\text{Ti}) = 80$ A MeV. [14] are shown along with the experimental data.

In Fig.3. the results of reactions $^9\text{Be}(^{50}\text{Ti}, x), E(^{50}\text{Ti}) = 80\text{A MeV}$ are fitted, that is, for the same projectile as in Fig.2 but with ^9Be target instead of ^{181}Ta . It can be seen from figures 2 and 3 that our formalism can fit the existing data very well for both ^{181}Ta and ^9Be target. In Fig.4. we have shown the full spectrum of the predicted production cross-sections of Si fragments for three different Ca projectiles viz. $^{42}\text{Ca}, ^{50}\text{Ca}, ^{58}\text{Ca}$. A comparison of the earlier parametrization (dotted lines) with the present one (solid lines) is shown here. It can be seen that the earlier parametrization tends to overestimate in the n-rich side and the extent of the overestimation increases as the projectile or the fragment of interest become more exotic.

To illustrate the point further and in a more quantitative fashion, we compare the ratio $\frac{\sigma_{old}}{\sigma_{new}}$, where σ_{old} and σ_{new} are the cross-sections for fragment production as calculated on the basis of the earlier and the present parametrization respectively, for two cases :

1. production of ^{35}Si and ^{40}Si from the projectile ^{50}Ca
2. production of ^{40}Si from projectiles ^{50}Ca and ^{58}Ca .

In the first case the extent of overestimation (the ratio) increases from a factor of 3 for ^{35}Si to a factor of 35.5 for the more exotic fragment ^{40}Si . For the second case the factor increases from 35.5 in the ^{50}Ca projectile case to about 52.2 in the case of more exotic projectile ^{58}Ca . Thus the discrepancy between the earlier and the present formalism becomes very serious in the RIB case where one needs to address the question of production of very exotic species from exotic projectiles.

In Fig.5 the maximum exoticity of the fragments (Si) are plotted against the corresponding projectile's (Ca) exoticity for two different cross-section limits viz. 0.01 mb and 1.0 mb. That is to say, given the lower limit of cross-section the exoticity of the maximum exotic Si isotope that can be produced from the fragmentation of a given Ca isotope is plotted as a function of exoticity of the Ca isotopes. Results for both the earlier and the present formalism are shown. It is evident that with the relaxation of the cross-section limit more exotic fragments are produced which is expected, although, the n-drip line is ($\rho_F = 0.71$ for Si) never reached with 0.01 mb cross-section limit. Calculation with present

parametrization shows that the n-drip line can be reached with cross-section in the range $0.001 \leq \sigma \leq 0.01$ mb for projectile exoticities greater than 0.65, which means drip-line for Si can be reached only with ^{56}Ca or more exotic Ca projectile. Interestingly, as the projectile is made more and more exotic, the exoticity of the fragment increases and ultimately shows a saturation tendency. The flat portion for projectile exoticities beyond the drip line (for Ca, $\rho_P=0.75$ at drip line which corresponds to ^{58}Ca) is a consequence of the factor ξ^d in the charge distribution. This tends to limit the usefulness of going for very neutron rich projectile beams. The earlier formalism predicts a much steeper increase of the fragment exoticity with the projectile exoticity and thus overestimates as compared to the present formalism, the advantage of RI projectiles for the production of new n-rich species.

The main interest of the present work has been to develop a formalism which can be used to predict reliably the production cross-sections of n-rich products from n-rich RIBs. However, to see how well the present formalism can predict cross-sections for the production of p-rich nuclei we have also considered the systems $^{58}\text{Ni}(^{78}\text{Kr}, X)$, $E(^{78}\text{Kr}) = 75\text{A MeV}$ [15] and $^{27}\text{Al}(^{86}\text{Kr}, X)$, $E(^{86}\text{Kr}) = 70\text{A MeV}$ [16], for which the experimental cross-section values for a large number of p-rich nuclei are available in the range $Z = 30$ to $Z = 38$ and $Z = 33$ to $Z = 39$ respectively. The experimental data (solid points) of p-rich nuclei, the results of Summerer et al (dotted lines) and the results of the present formalism (solid lines) are shown in figures 6 and 7.

In the ^{78}Kr projectile case (Fig.6), calculations based on Summerer et al formalism give a slight overall better match with the experimental cross-sections as compared to predictions based on the present formalism. However, in the case of ^{86}Kr projectile (Fig.7), the present formalism reproduces the experimental data much better than the predictions of Summerer et al. It is important to note that ^{78}Kr is rather a p-rich projectile in contrast to ^{86}Kr , which is slightly n-rich (although both are β -stable isotopes of Kr). This, together with the results in case of rather n-rich projectiles ^{48}Ca and ^{50}Ti , show that, while our formalism can predict accurately the cross-sections of fragments produced from n-rich projectiles, the predictions are not so accurate for fragments produced from p-rich projectiles.

In case of ^{86}Kr projectile our formalism can not predict accurately the cross-sections of Rb and Sr isotopes, although the matching is much better as compared to the predictions of the earlier formalism. Especially in the case of Sr-isotopes the difference between the prediction and the experimental data is more than an order of magnitude. However, we note that production of Sr-isotopes from Kr-projectile involves two proton pick-up reactions and therefore, the production cross-sections should have a significant component from the pick-up reaction. This might explain the poor matching in the case of Sr-isotopes.

To examine how well our formalism can reproduce the experimental data at higher energies we have plotted in Fig.

8, the experimental cross-sections of isotopes of different elements from Ca to Kr, produced in 500 A MeV ^{86}Kr [17] along with the estimations based on the present formalism as well as the earlier formalism.

In order to have a fairly good agreement with the experimental data we need to use a value of the exponent U of the charge distribution equal to 1.4 instead of 1.57 which was used in the lower energy (≤ 100 A MeV) domain. As is evident from Fig.8, the agreement with the experimental data is not as excellent as it has been the case at energies below 100 A MeV.

At present no experimental data is available for the production cross-sections of very n-rich exotic fragments from ^{86}Kr projectile. The availability of such data would have allowed us to check the accuracy of the predictions of the present formalism for projectiles upto $A \sim 100$. The present formalism predicts a value of 7pb, 2.2pb and 180 pb for the cross-section of ^{78}Ni produced by the fragmentation of ^{86}Kr , ^{98}Kr and ^{86}Ge respectively. The cross-section values clearly indicate that the use of a more exotic projectile leads to higher cross-section for production only when its mass number is not far away from the fragment's mass number. This is an artefact of the $(A_P - A_F)^{1/3}$ dependence of the width (R^{-1}) which tends to compensate the gain in the cross-section due to the increase in exoticity of the projectile by the corresponding loss due to decrease in the width.

IV. CONCLUSION.

In this article we have attempted to develop an empirical formalism for estimating the cross-sections of exotic fragments produced from exotic projectiles (RIBs). In the present formalism we have assumed following earlier prescriptions the factorizability of the production cross-section. The charge distribution part of the earlier formalism [6] has been thoroughly modified in the present work, while the expression for the mass yield has been kept unchanged.

It has been shown that the present (modified) formalism can reproduce accurately the recent experimental data for the production of a number of neutron-rich species from ^{48}Ca and ^{50}Ti projectiles. The present formalism can, therefore, be used to predict much more reliably the production cross-section of new n-rich nuclei produced by fragmentation of n-rich radioactive projectiles.

A number of physically appealing and transparent new parameters are introduced in the expression for charge distribution in our formalism. The introduction of exoticity parameters for the projectile and the fragment to take care of the so called 'memory' effect is one of them. The excellent matching with the experimental data (Fig.1 and 2) for n-rich exotic fragments justifies further their inclusion. Moreover, the representation in terms of the exoticity

of the fragment and the projectile clearly brings out how much one can expect to gain in terms of production of more exotic species by using a more exotic projectile. The fact that the slope of this curve is rather flat irrespective of the lower limit of the cross-section one has considered, tends to offset some of the advantages of using very n-rich projectiles for the production of new n-rich nuclei.

The introduction of $(A_P - A_F)^{1/3}$ dependence of the width parameter R represents another new physics input which has been introduced to take care of the intuitive expectation that the width of the charge distribution should depend on the fraction of the projectile that has been chopped out in the fragmentation reaction. This dependence is crucial for having a uniform good matching with the experimental cross-sections over a wide range of fragments produced from the same projectile, e.g. in the case of production of different isotopes of all elements between oxygen and silicon from the fragmentation of ^{48}Ca (Fig.1). Furthermore, this factor tends to offset the advantage (higher production cross-section) of using more and more exotic projectiles of a given atomic number for the production of a given n-rich exotic fragment of interest.

Although, the present formalism results in a much better overall fit with the experimental data for a variety of projectiles and projectile energies as compared to the earlier formalism [6], the agreement is not equally good in all cases. For example, the agreement is not very satisfactory for fragments produced from ^{78}Kr . The same is true for fragments produced from the fragmentation of ^{86}Kr at 500 A MeV. While a better agreement in these cases would certainly have been a more desirable feature, the main interest of the present work has been to develop an empirical formalism which can be used to predict reliably the production cross-sections of n-rich nuclei produced from fragmentations of n-rich radioactive projectiles. The present formalism is expected to be quite good for the said purpose.

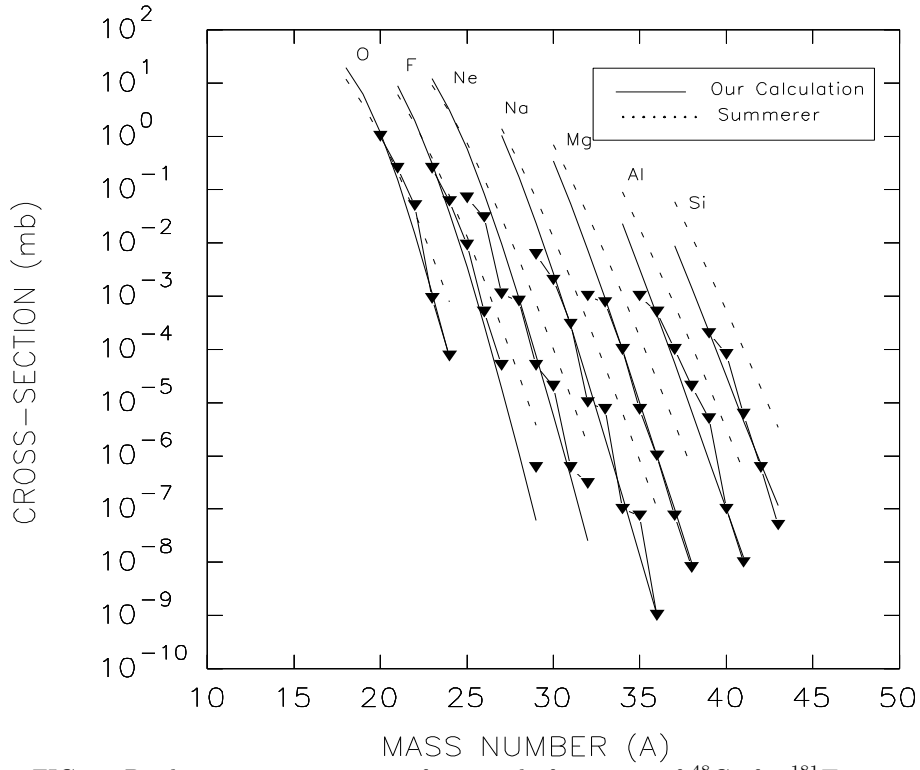


FIG. 1. Production cross-sections of projectile fragments of ^{48}Ca for ^{181}Ta target, compared with those calculated by the old and modified parametrizations.

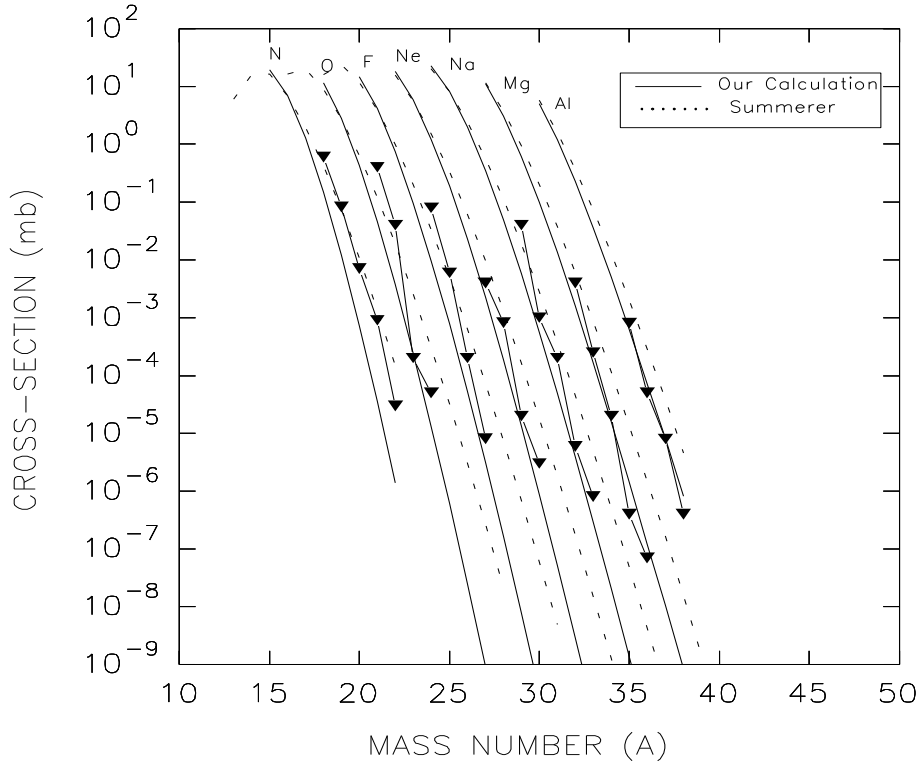


FIG. 2. same as Fig.1. with ^{50}Ti as projectile.

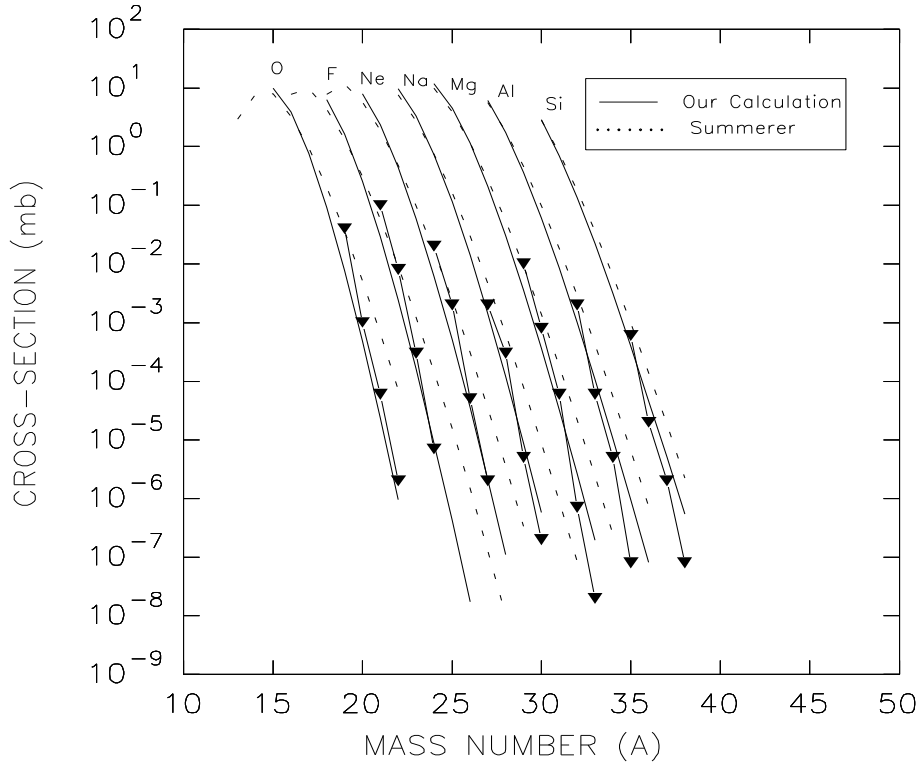


FIG. 3. same as Fig.2.with the same projectile but ${}^9\text{Be}$ as target

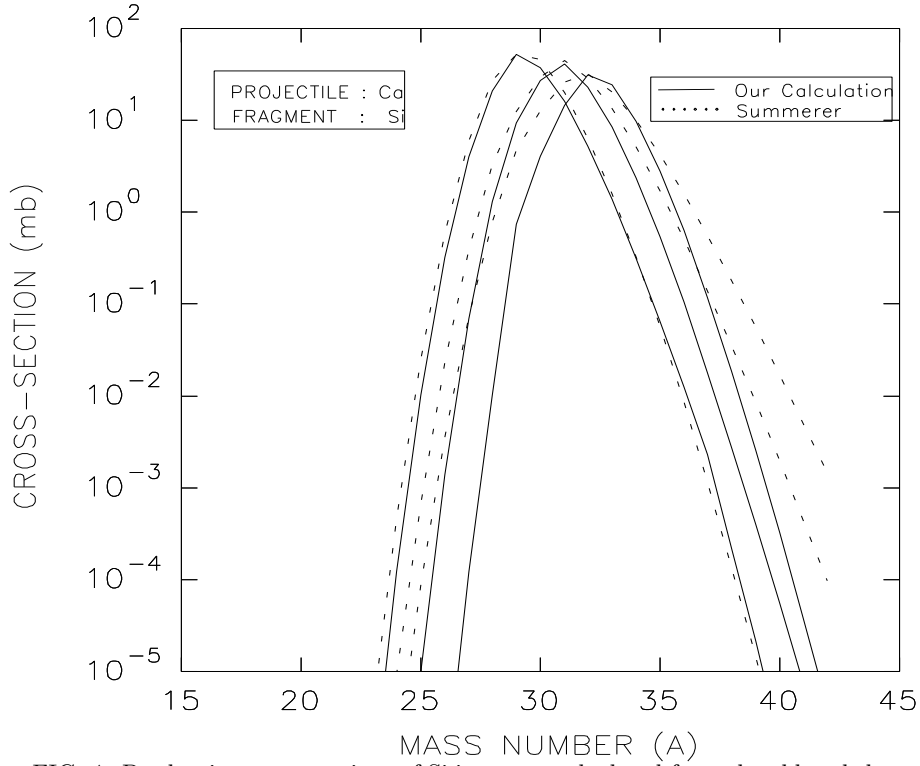


FIG. 4. Production cross-sections of Si isotopes, calculated from the old and the modified parametrization for three different Ca projectiles viz. ${}^{42}\text{Ca}$, ${}^{50}\text{Ca}$, ${}^{58}\text{Ca}$.

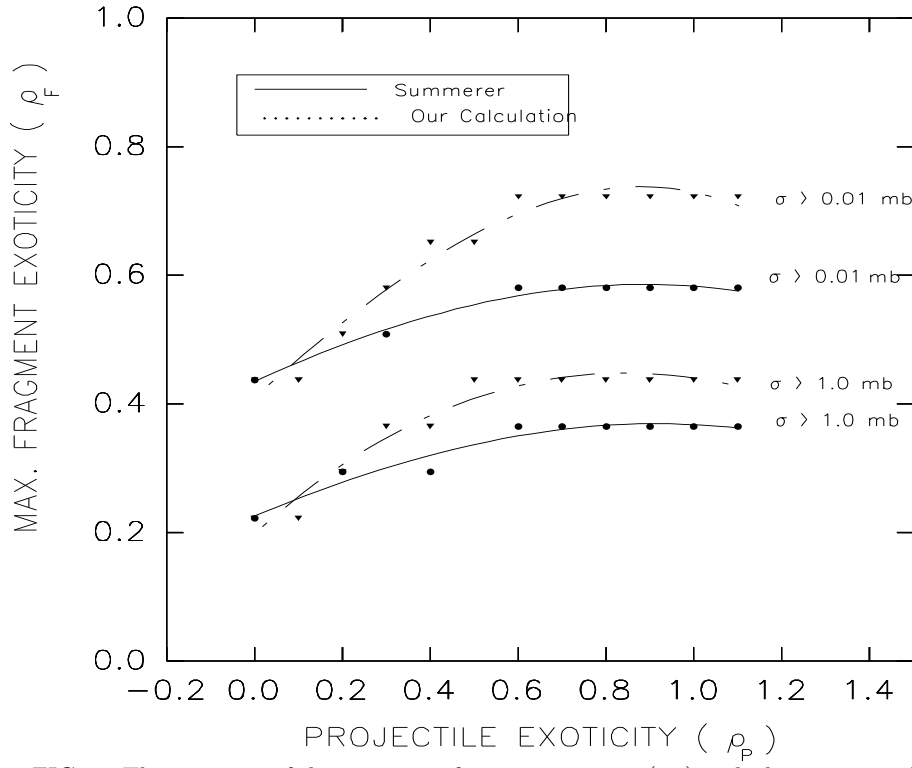


FIG. 5. The variation of the maximum fragment exoticity(ρ_F) with the exoticity of the projectile for the old and the modified formalism in the n-rich side.

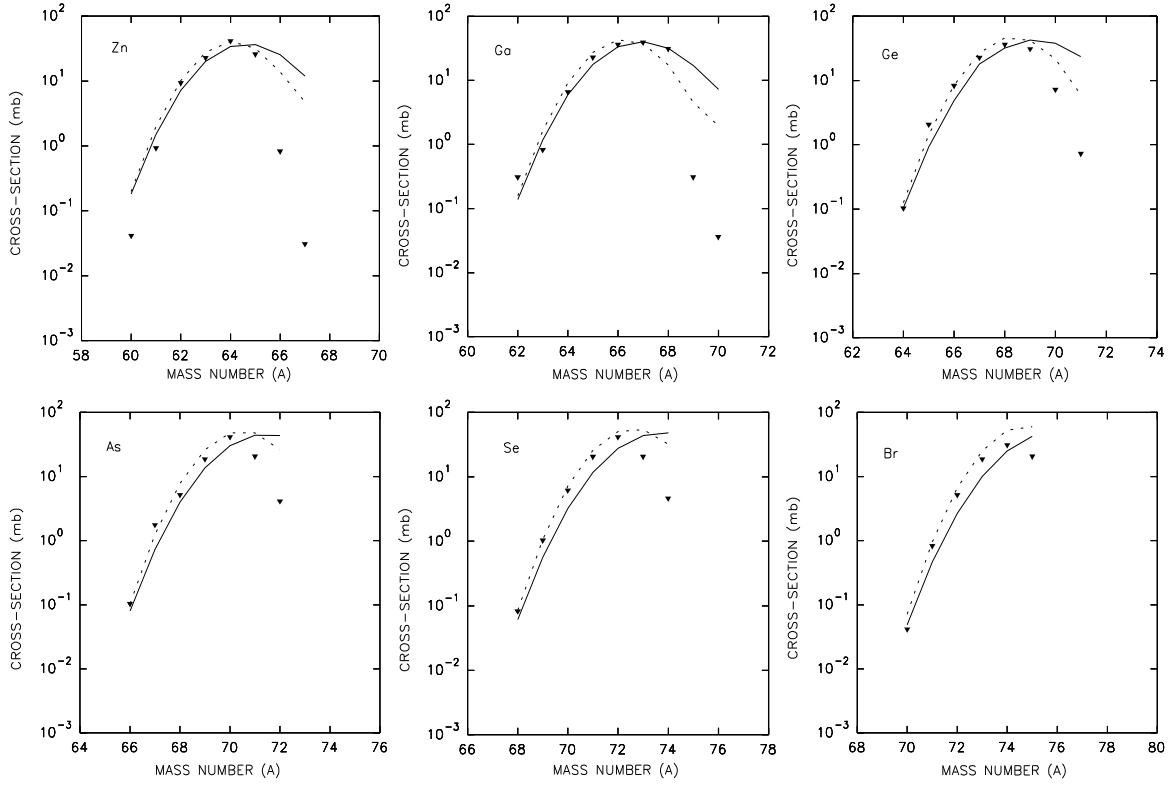


FIG. 6. Isotopic cross-section for the elements between Zinc and Bromine from the reaction $^{78}\text{Kr} + ^{58}\text{Ni}$ at 75 A MeV. The solid points indicate the measured production cross-sections. The dotted lines represent the parametrization by Summerer et al, while the solid line represent our calculation.

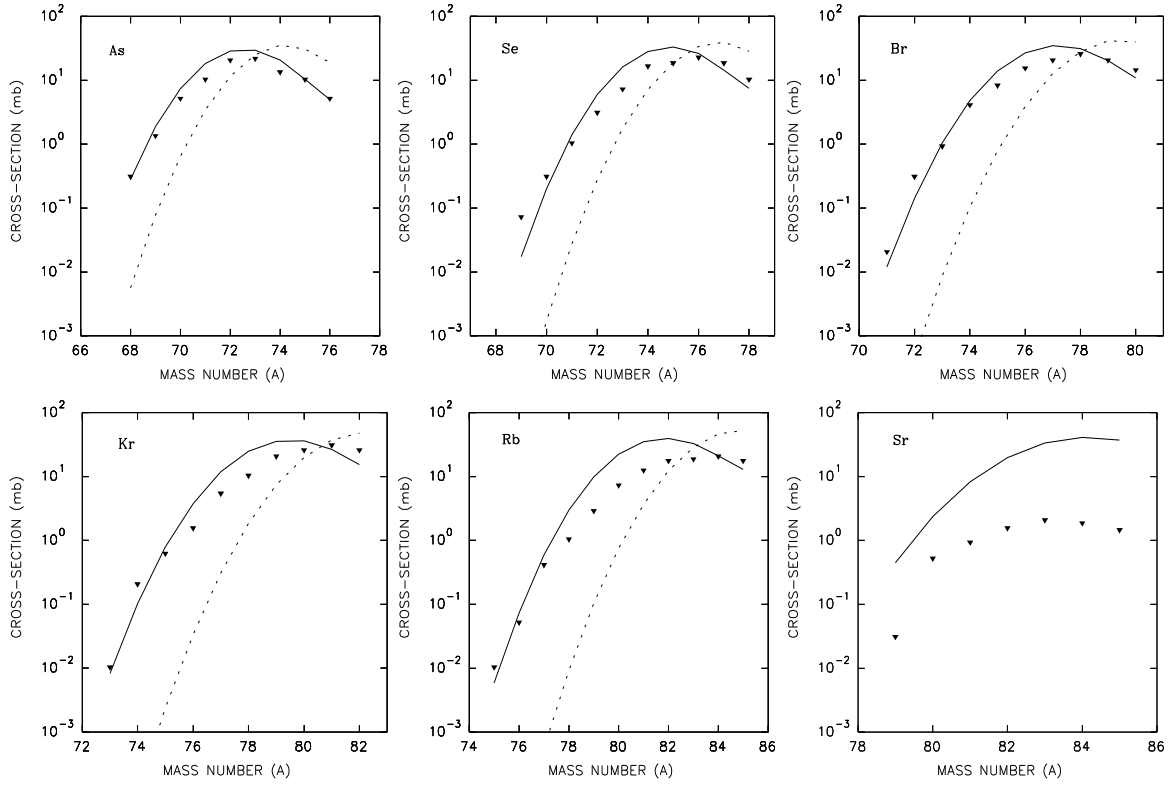


FIG. 7. Similar to Fig.6, but for different reaction : $^{86}\text{Kr} + ^{27}\text{Al}$ at 70 A MeV.

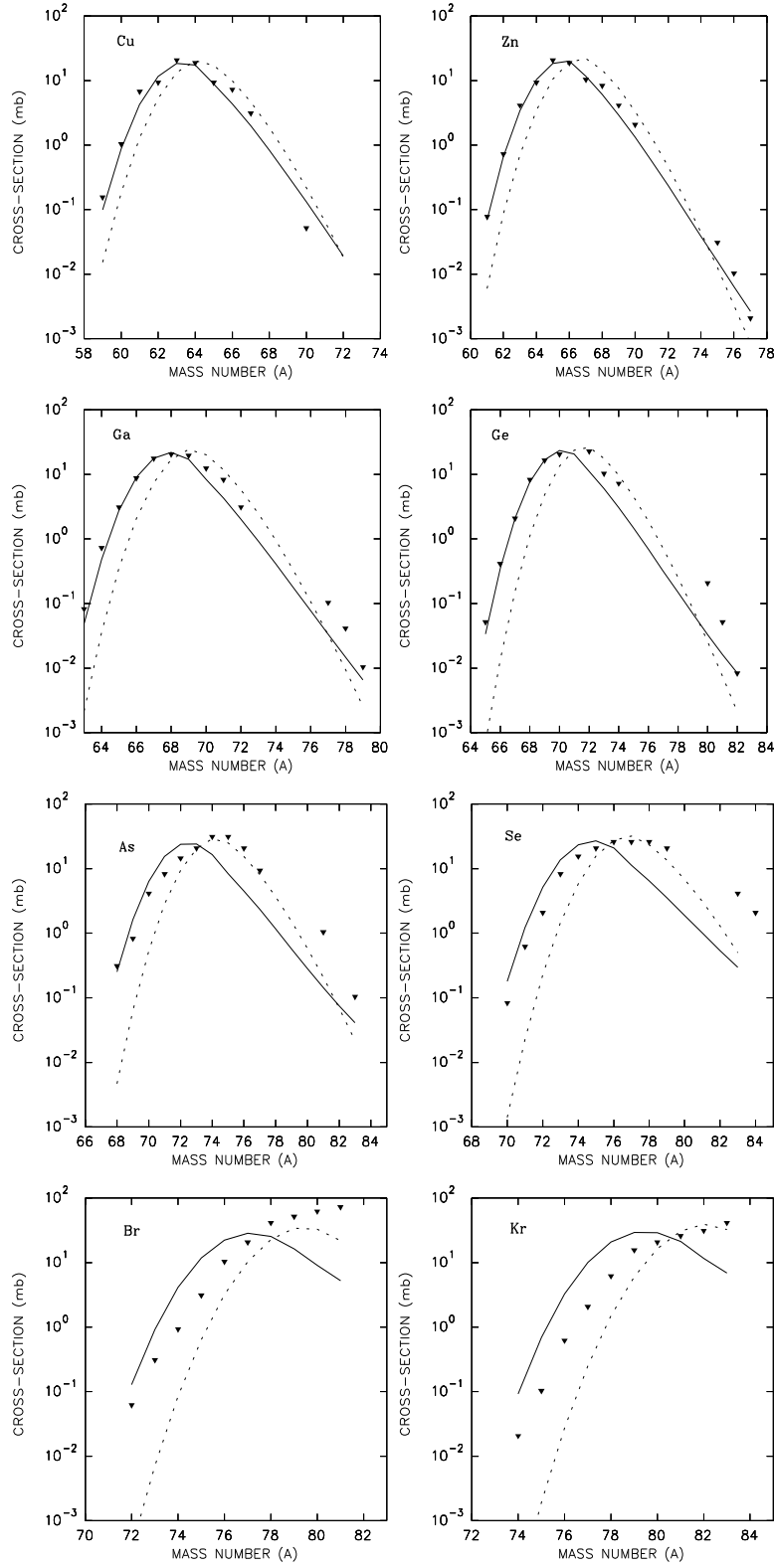


FIG. 8. Isotopic cross-sections for elements between copper ($Z=29$) and Krypton ($Z=36$) from the reaction : $^{86}\text{Kr} + ^9\text{Be}$ at 500 A MeV. The solid points indicate the measured production cross-sections. The dotted lines represent the parametrization by Summerer et al, while the solid line represent our calculations.

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